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THE THEORY OF THE CRITICAL CONDITIONS OF A GAS EJECTOR AT LARGE PRESSURE DROPS

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13. ABSTRACT

The critical operating conditions of an ejector with a cylindrical mixing chamber are analyzed within the framework of ideal-gas dynamics. Jet flows, overexpanded with respect to the static pressure of a low-pressure gas, are calculated on the basis of supersonic compressed layer theory. The calculations confirm the experimental finding that the degrees of compression attainable in ejectors in the presence of large pressure gradients exceed the limiting analytical values obtained from theories developed for moderate pressure gradients.

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Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH

DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}
rot	curl
lg	log

THE THEORY OF THE CRITICAL CONDITIONS OF A GAS EJECTOR AT LARGE PRESSURE DROPS

V. N. Gusev

Within the dynamics of ideal gas there is investigated the critical operating conditions of a gas ejector with cylindrical mixing chamber at large pressure drops. For calculation of flow in the jet, overexpanded relative to the static pressure of low-pressure gas, the theory of hypersonic compressed layer is used. The performed calculations confirm the fact established earlier experimentally (G. L. Grodzovskiy, Bulletin of Academy of Sciences USSR. MZhG, 1968, No. 3) that with large pressure drops the attainable compression ratios in ejectors exceed the maximum computed values being given by theories developed for the case of moderate pressure drops.

The phenomenon of chocking in a supersonic gas ejector was studied for the first time by M. D. Millionshchikov and G. I. Ryabinkov [1]. In the subsequent works of G. I. Taganov, I. I. Mezhirov, A. A. Nikol'skiy, V. I. Shustov, Yu. N. Vasil'yev and V. T. Kharitonov [2], [3] the theory of critical conditions underwent considerable refinement. With moderate pressure drops the basic parameters of the gas ejector, obtained by calculation, were in good conformity with the results of experiment. Taking into account the mixing of ejecting and ejected flows the critical operating conditions of the gas ejector were examined in [4]-[6].

Below within the theory of the flow of ideal gas there is investigated the critical operating conditions of the gas ejector at large pressure drops.

Let us examine the gas ejector with cylindrical mixing chamber, operating at critical conditions (Fig. 1). Section 1 corresponds to the inlet to the mixing chamber, section 3 - to its exit, section 2 is the chocking section, in which during operation at critical conditions the velocity of the ejected gas becomes equal to the speed of sound. It is assumed that at the end of the mixing chamber there is accomplished full mixing of gases. Let us introduce the following designations.

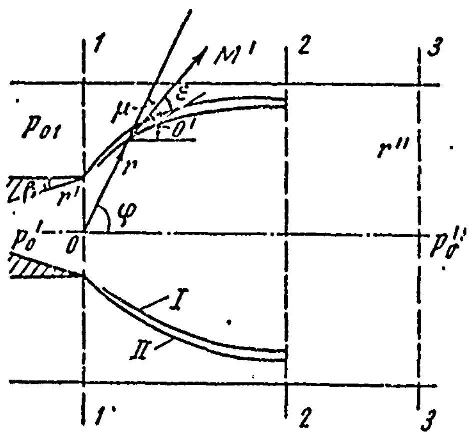

Fig. 1.

Let p_0' - the total pressure of high-pressure gas; p_{01} - the total pressure of low-pressure gas; p_0'' - the total pressure of the mixture exiting the ejector; $k_* = G_1/G'$ - the critical ejection factor, equal to the ratio of mass flow rate G_1 of the ejected gas to mass flow rate G' of the ejecting gas under chocking conditions. The geometric dimensions of the ejector are determined by radius r' of the jet of high-pressure gas in section 1 and by radius r'' of the mixing chamber. Let us designate the M number of high-pressure gas in section 1 by M_1'.

We will pause on the features of the discharge of the high-pressure gas jet at large pressure drops. Since the static pressure of high-pressure gas in section 1 is greater than static pressure of low-pressure gas in this section, the expansion of gas occurs outside the nozzle and is extended in the flow along the rarefaction wave centered on the nozzle discharge edge. The considerable zone of flow in the jet becomes overexpanded relative to the static pressure of low-pressure gas. The flow in this region will approach the flow from some equivalent source whose intensity changes upon transition from one beam to another [7]. The

overexpansion ratio of flow in the jet will be determined by the system of shock waves bounding the overexpanded region of flow. The gas, having passed through the suspended shock wave 1 (see Fig. 1), forms the compressed layer adjacent to the shock, which concentrates a large part of the high-pressure gas [7]. Thus, the gas flow in the high-pressure jet of the gas ejector will be not only nonuniform, but also will consist, generally speaking, of two qualitatively different flows. It is obvious that such a flow cannot be described within the hydraulic theories.

With sufficiently large values of $\overline{p}'_0 = \frac{p'_0}{p_{01}}$ for the contour of the compressed layer it is possible to write [7]:

$$\frac{d^2 f}{d\varphi^2} = f + \frac{2}{f}\left(\frac{df}{d\varphi}\right)^2 - \frac{2\pi r'^2 p'_0}{QU_m}\sin\varphi\left[f^2 + \left(\frac{df}{d\varphi}\right)^2\right]^{\frac{3}{2}} \times$$
$$\times\left[\frac{p}{p'_0} - \frac{2\gamma}{\gamma+1}M'^2\sin^2\varepsilon\left(\frac{\gamma-1}{2}M'^2\right)^{-\frac{\gamma}{\gamma-1}}\right], \qquad (1)$$

where

$$\varepsilon = \mu - (\varphi - \theta'),\ \mu = \mathrm{arctg}\left(-f \Big/ \frac{df}{d\varphi}\right).$$

Here r, ϕ - polar coordinates with pole at point O (see Fig. 1), $f(\phi) = \frac{r}{r'}$ - the contour of shock, ε - shock wave angle to the direction of incoming flow, μ - the angle formed by the direction of radius vector r and by the direction of the tangent to the outline of shock, Q - the total gas flow rate through the compressed layer, U_m - terminal velocity, M' and θ' - M number and velocity vector angle before the shock wave surface in high-pressure gas, p - variable pressure on the outer edge of the compressed layer, γ - the specific heat ratio in high-pressure gas.

Assuming the flow of low-pressure gas one-dimensional, for pressure on the outer edge of the compressed layer II (see Fig. 1) we have:

$$p \ [illegible]\ p_0\left(1 + \frac{\varkappa - 1}{2} M^2\right)^{[illegible]}; \qquad (2)$$

M is determined fr[illegible]

$$M\left(1+\frac{\varkappa-1}{2}M^2\right)^{-\frac{\varkappa+1}{2(\varkappa-1)}}=$$

$$=M_1\left(1+\frac{\varkappa-1}{2}M_1^2\right)^{-\frac{\varkappa+1}{2(\varkappa-1)}}\left[\left(\frac{r''}{r'}\right)^2-1\right]\left[\left(\frac{r''}{r'}\right)^2-(f\sin\varphi)^2\right]^{-1}.$$

Here M_1 - M number of low-pressure gas in section 1, κ - the specific heat ratio in low-pressure gas.

By substituting (2) in equation (1), for the contour of the high-pressure jet we will finally obtain:

$$\frac{d^2f}{d\varphi^2}=f+\frac{2}{f}\left(\frac{df}{d\varphi}\right)^2-\frac{2\pi r'^2 p_0'}{Q\bar{U}_m}\sin\varphi\left[f^2+\left(\frac{df}{d\varphi}\right)^2\right]^{\frac{3}{2}}\times$$

$$\times\left[\left(\frac{p_{01}}{p_0'}\right)\left(1+\frac{\varkappa-1}{2}M^2\right)^{-\frac{\varkappa}{\varkappa-1}}-\frac{2\gamma}{\gamma+1}M'^2\sin^2\varepsilon\left(\frac{\gamma-1}{2}M'^2\right)^{-\frac{\gamma}{\gamma-1}}\right]. \qquad (3)$$

The values of Q, M' and θ' entering the equation are functions of polar coordinates and parameters M_1', β, γ. When f >> 1 for them the asymptotic dependences, given in [7], are valid. These functions were determined numerically by method of characteristics according to the program compiled on the basis of the scheme of calculation and formulas presented in [8]. The boundary conditions of the problem have the form [7].

$$f=1,\ \frac{df}{d\varphi}=f'_{*1}\ \text{when}\ \varphi=\frac{\pi}{2}, \qquad (4)$$

where

$$f'_{*1}=\frac{-M_{*1}^2\sin 2\theta_{*1}+\left[M_{*1}^4\sin^2 2\theta_{*1}-4\left(M_{*1}^2\cos^2\theta_{*1}-1\right)\left(M_{*1}^2\sin^2\theta_{*1}-1\right)\right]^{\frac{1}{2}}}{2\left(M_{*1}^2\cos^2\theta_{*1}-1\right)};$$

$$\theta_{*1}=\beta-\left\{\left(\frac{\gamma+1}{\gamma-1}\right)^{\frac{1}{2}}\operatorname{arctg}\left[\left(\frac{\gamma-1}{\gamma+1}\right)^{\frac{1}{2}}\sqrt{M_{*1}^2-1}\right]-\operatorname{arctg}\sqrt{M_{*1}^2-1}\right\}-$$

$$-\left\{\left(\frac{\gamma+1}{\gamma-1}\right)^{\frac{1}{2}}\operatorname{arctg}\left[\left(\frac{\gamma-1}{\gamma+1}\right)^{\frac{1}{2}}\sqrt{M_1'^2-1}\right]-\operatorname{arctg}\sqrt{M_1'^2-1}\right\};$$

$$M_{*1}=\sqrt{\frac{2}{\gamma-1}\left[\bar{p}_0'^{-\frac{\gamma-1}{\gamma}}\left(1+\frac{\varkappa-1}{2}M_1^2\right)^{\frac{\varkappa(\gamma-1)}{\gamma(\varkappa-1)}}-1\right]}.$$

With assigned drop $\bar{p}_0'$ and geometry of ejector r"/r' the integration of equation (3) was performed at several values of M_1 until in section 2 at u = φ the M number of low-pressure gas reached the speed of sound.

After determining M_1 for the critical ejection factor it is possible to write

$$k_* = \frac{q(\lambda_1)}{a\vartheta \bar{p}_0' q(\lambda_1')}. \tag{5}$$

By adding to equation (5) the known equations of ejection

$$\left.\begin{aligned} \bar{p}_0'' &= \frac{q(\lambda_1) + a\bar{p}_0' q(\lambda_1')}{(1+a)\, q(\lambda'')} \sqrt{1 + k_*\vartheta \frac{z(\vartheta) - 2}{(1 + k_*\vartheta)^2}}\,; \\ z(\lambda'') &= \frac{q(\lambda_1) z(\lambda_1) + a\bar{p}_0' q(\lambda_1') z(\lambda_1')}{q(\lambda_1) + a\bar{p}_0' q(\lambda_1')} \left[1 + k_*\vartheta \frac{z(\vartheta) - 2}{(1 + k_*\vartheta)^2}\right]^{-\frac{1}{2}}, \end{aligned}\right\} \tag{6}$$

we will obtain the complete system of equations which determines the parameters of the ejector operating in critical conditions. In the last relationships there has been accepted: λ - normalized velocity, ϑ - critical velocity ratio of ejecting and ejected gases, $q(\lambda)$, $z(\lambda)$ - gas-dynamic functions, $\bar{p}_0'' = \frac{p_0''}{p_{01}}$ - the compression ratio of ejector, $a = \left[\left(\frac{r''}{r'}\right)^2 - 1\right]$.

Figure 2 depicts dependences of $\bar{p}_0''$ on $\bar{p}_0'$ at different values of k_* and $(r''/r')^2 \geq 20$ when $\gamma = \kappa = 1.4$, $M_1' = 1$, $\vartheta = 1$ and $\beta = 0$ (solid curves).

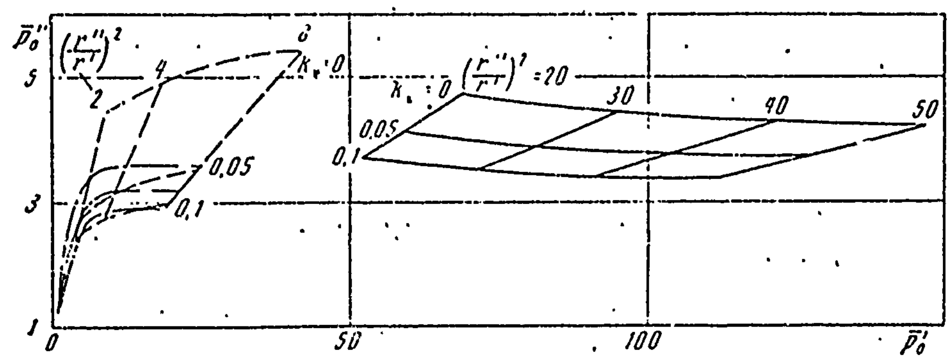

Fig. 2.

At smaller values of $(r''/r')^2$ the calculations were not performed, since here the conditions of applicability of the theory of hypersonic compressed layer are disturbed. For comparison on this figure at the same values of k_* there are given experimental data borrowed from [6] (dotted curves), and calculated - according to the theory of critical conditions [2] (dot-dash curves).

As follows from Fig. 2, the performed calculations confirm the fact established earlier experimentally [6] that at large pressure drops $\bar{p}_0'$ the attainable compression ratios in the ejectors exceed the maximum computed values according to theory [2]. With this the maximum compression ratio of the ejector will be realized at larger values of $\bar{p}_0'$ than according to theory [2].

Let us pause on case $k_* = 0$, which determines the maximum compression ratio of the ejector at assigned pressure drop $\bar{p}_0'$. In this case the M number of low-pressure gas at the mixing chamber inlet $M_1 = 0$, and the critical operating conditions of the ejector in the accepted statement will be determined from the natural condition of expansion of jet of high-pressure gas to the transverse dimension of the mixing chamber r". In this case the total pressure of low-pressure gas p_0' will be equal to the external pressure in space, where the jet escapes. At large values of pressure drops $\bar{p}_0' = \frac{p_0'}{p_{01}}$ the discharge of such jets into space with constant pressure was examined in [7]. With the specific heat ratio in high-pressure gas $\gamma = 1.4$, $M_1' = 1$ and $\vartheta = 1$ these data (solid curve) together with experimertal (triangles), borrowed from [9], have been presented in Fig. 3 in the form of the relationship of maximum distance r"/r' of the suspended shock wave from the axis of the jet to pressure drop $\bar{p}_0' = \frac{p_0'}{p_{01}}$ on the assumption that the thickness of the compressed layer adjacent to the shock is neglible. Here are provided values r"/r' for a series of sonic ejectors operating in critical conditions when $k_* = 0$ (small circles - experiment [6], dotted curve - theory of critical condition [2]). Comparison shows that with an increase of pressure drop $\bar{p}_0'$ the experimental values of r"/r' will depart from the theoretical dependence [2], approaching values of r"/r' determined with respect to the maximum distance of the suspended shock wave from the axis of the jet during its discharge into space with constant pressure.

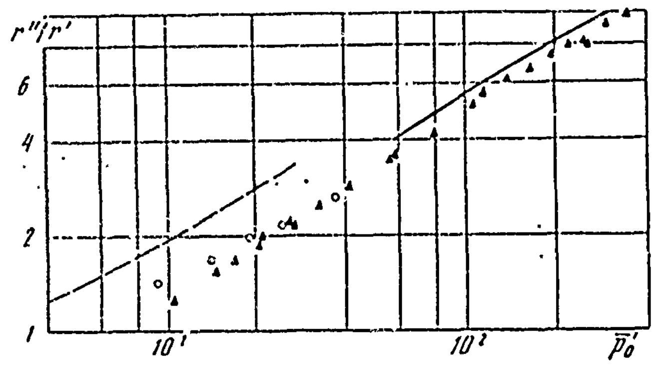

Fig. 3.

When $k_* = 0$ system (6) for calculation of the compression ratio of the ejector is converted to form

$$\left.\begin{aligned} \overline{p}_0'' &= \frac{\alpha \overline{p}_0' q(\lambda_1')}{(1+\alpha)\, q(\lambda'')}; \\ z(\lambda'') &= z(\lambda_1') + \frac{\left(\frac{\gamma+1}{2}\right)^{\frac{1}{\gamma-1}}}{\alpha \overline{p}_0' q(\lambda_1')}. \end{aligned}\right\} \qquad (7)$$

In the case of sonic ejector ($M_1' = 1$) and $\gamma = 1.4$ the results of calculations of the maximum compression ratio of the ejector depending on $\overline{p}_0'$ when $k_* = 0$ are given in Fig. 2. From the comparison of the findings with experimental [6] it follows that dependence $\overline{p}_0''(\overline{p}_0')$ when $k_* = 0$ has a maximum at finite value $\overline{p}_0'$ and when $\overline{p}_0' \to \infty$ it approaches constant.

Let us determine the limiting values of the compression ratio of the ejector when $k_* = 0$ in the case of infinite pressure drops $\overline{p}_0'$. For the values of r''/r' entering the equations of ejection (7) determined here with respect to the maximum distance of the suspended shock wave from the axis of the jet during its discharge in space with constant pressure, from [7] follows:

$$\left(\frac{r''}{r'}\right)^2 = \xi(\gamma, \beta, M_1')\, \overline{p}_0'. \qquad (8)$$

When $\overline{p}_0' \gg 1$

$$\alpha = \left[\left(\frac{r''}{r'}\right)^2 - 1\right]^{-1} \approx \left(\frac{r''}{r'}\right)^{-2} = \frac{1}{\xi(\gamma, \beta, M_1')\, \overline{p}_0'}.$$

and ejection equations (7) taking into account (8) are converted to the form which does not depend upon $\bar{p}_0'$:

$$\left.\begin{aligned} \bar{p}_0'' &= \frac{q(\lambda_1')}{\xi(\gamma, \beta, M_1')\, q(\lambda'')}; \\ z(\lambda'') &= z(\lambda_1') + \frac{\left(\frac{\gamma+1}{2}\right)^{\frac{1}{\gamma-1}} \xi(\gamma, \beta, M_1')}{q(\lambda_1')}. \end{aligned}\right\} \qquad (9)$$

In the case of $\gamma = 1.4$ and $\beta = 0$ at values of number $M_1' = 1$ and 3, for which the values of $\xi(\gamma, \beta, M_1')$ entering (9) were determined in [7], the limiting values of the compression ratio of the ejector when $k_* = 0$ are given in the table

M_1'	ξ	$\bar{p}_0''$
1	0,37	3,76
3	0,033	10,5

Comparison shows that when $p_0' \gg 1$ the transition from sonic ejector to supersonic leads to a considerable increase in the compression ratio of the ejector.

In conclusion the author thanks T. V. Klimova for help in conducting the necessary calculations.

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